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POLARIZATION MEASUREMENTS OF MARS AND MERCURY: RAYLEIGH SCATTERING IN THE MARTIAN ATMOSPHERE*

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ABSTRACT

Ground-based polarimetric data taken near maximum elongation are presented. These data are analyzed on the assumption of an optically thin, Rayleigh-scattering atmosphere, and a surface whose polarization varies inversely as surface albedo. For Mars, the best fit to the data yields an estimate of surface pressure in the range 4–7.5 mb, if CO_2 is the principal constituent. There is no need to postulate the existence of fine dust in the Martian atmosphere. For Mercury, the best fit to the data yields an upper limit on Rayleigh scattering equal to 0.001 of the Earth's atmosphere.

I. INTRODUCTION

This paper is a report of polarization measurements of Mars and Mercury at 200 Å resolution from 3200 to 7000 Å. The aim of the study was to measure the amount of Rayleigh scattering in these planets' atmospheres. For Mars, these and previous data are consistent with a model in which there is 4–7.5 mb of CO_2, with no permanent atmospheric haze. For Mercury, the data are consistent with a model in which there is no detectable atmosphere.

As a result of this work, it appears that previous polarimetric data have been misinterpreted. For many years, the Martian surface pressure was believed to be about 80 mb, mainly on the basis of polarimetric data (Dollfus 1961). This was revised downward several times (Dollfus and Focas 1966; Pollack 1967), but the resulting figures were still much larger than the estimates of 5–7 mb from radio-occultation data (Kliore *et al.* 1965; Kliore *et al.* 1969). The occultation data are generally accepted, and so the polarimetric data have recently been cited as evidence of fine haze or aerosol in the Martian atmosphere (Dollfus and Focas 1969; Morozhenko 1970). However, previous studies either failed to consider data at the shortest wavelengths (Dollfus and Focas 1966) or failed to take into account the polarization of light reflected by the surface at the shortest wavelengths (Morozhenko 1970). These errors are corrected in the present study, and the estimate of surface pressure now agrees with the occultation value.

Similarly, polarization data have been cited as evidence of an atmosphere on Mercury with about 0.003 of the scattering power of the Earth's atmosphere (Dollfus 1961). However, these data were reexamined (O'Leary and Rea 1967), and this figure was changed to an upper limit. The present study gives an improvement by a factor of 3 in this limit because measurements made at ultraviolet wavelengths are considered in the analysis.

The main difficulty in analyzing the data is separating out the effect of the planet's atmosphere from that of the surface. Thus one needs a model based on laboratory experiment and observation which restricts the number of free parameters of the problem. Treating the atmosphere as a layer of Rayleigh scatterers is one such assumption; a single free parameter then describes the amount of light scattered by the atmosphere and its polarization at all wavelengths.

For the surface, one must rely on empirical formulae relating polarization of scattered light and albedo. For most surfaces, an inverse relation exists; that is, for a given viewing

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geometry the degree of polarization and albedo of the surface vary with wavelength such that when one is large, the other is small, and vice versa. Specifying the precise form of this relationship is the major source of uncertainty in this study; errors of observation are relatively less important. Nevertheless, one can place reasonable limits on the surface polarization of Mars and Mercury on the basis of observations of the Moon (Gehrels, Coffeen, and Owings 1964) and of powders in the laboratory (Dollfus 1961; Coffeen 1965). When this is done, a reasonable determination of the Rayleigh-scattering optical depth can be made.

The observations themselves are relatively straightforward. One measures the degree of polarization of light scattered by the planet near maximum elongation at a number of wavelengths. The polarization is assumed to be linear; its direction is found to be perpendicular to the plane of scattering, which is the plane containing the Sun, the planet, and the Earth. For Mars, the observations were made at $\theta = 42.5°$, where θ is the phase angle between the Sun and the Earth in the Martian sky; for Mercury, the observations were made at $\theta = 105°$. The data agree with those published by other observers at all wavelengths where a comparison is possible. The main differences between this and previous studies are the full wavelength coverage, the systematic treatment of surface polarization, and the conclusions derived from the analysis.

II. METHOD OF ANALYSIS

A number of simplifications are possible if the surface albedo and atmospheric optical depth are both small. First, the atmosphere and surface may be treated separately; one may neglect the illumination of the atmosphere by the surface and that of the surface by the atmosphere. Second, only first-order scattering, directly out of the incident solar beam, is important; and third, the attenuation of the incident beam as it passes through the atmosphere can be neglected. These assumptions are verified a posteriori. The fact that the planetary albedos of both Mars and Mercury are low is consistent with these assumptions.

Let the light scattered at a point on the planet be resolved into components whose electric vectors are perpendicular and parallel to the plane of scattering, respectively. If $I_\perp$ and $I_\parallel$ are the intensities of these components, then the degree of polarization is

$$\delta = \frac{I_\perp - I_\parallel}{I_\perp + I_\parallel} . \tag{1}$$

The geometric albedo A of a point on the disk is the ratio of the total intensity $I_\perp + I_\parallel$ to the intensity of a perfect diffuse reflector facing the Sun at the same location in space. Thus if $\pi F_\odot$ is the solar flux at the planet in a specified wavelength interval, the albedo A is simply the total intensity in the interval divided by $F_\odot$. The geometric albedo of the planet p is the average of A over the entire disk, where the albedo of the unilluminated portion is taken to be zero.

Light from the planet consists of two components: that which has been scattered by the atmosphere and that which has been scattered by the surface, denoted by subscripts a and s, respectively. The surface component is assumed to obey a relation of the form

$$\log \delta_s = -m \log A_s + \log b ; \tag{2}$$

that is, at each value of the phase angle θ, both δ_s and A_s vary with wavelength according to equation (2) so that m and b are independent of wavelength. As stated in the Introduction, this relation appears to hold for the Moon and for most silicate powders. Values of m fall in the range

$$0.7 < m < 1.4 , \tag{3}$$

where the precise value depends on the chemical and physical properties of the surface. If the measurements refer to light from the entire planet, equation (2) may still be valid with the albedo A_s replaced by the surface component of the geometric albedo p_s. A sufficient condition for this to be valid is that the constant m and the spectral reflectivity $A_s(\lambda)/A_s(\lambda_0)$ be independent of position on the disk, for all wavelengths λ and λ_0. In what follows, it is assumed that these conditions are fulfilled.

The geometric albedos $p(\lambda, \theta)$ have been measured for Mars and Mercury at all wavelengths and phases of interest in this study (Irvine *et al.* 1968). However, these involve a contribution from the atmosphere p_a, which must be subtracted off before the geometric albedo of the surface p_s is known. This atmospheric contribution depends on the optical depth τ, which is defined as follows:

$$\tau = \frac{8\pi^3}{3\lambda^4} \frac{(n^2 - 1)^2}{N_0^2} \int_0^\infty N \, dZ \,, \tag{4}$$

where n is the index of refraction of the medium at standard temperature and pressure, N_0 is Loschmidt's number, Z is the vertical coordinate, and N is the number density of molecules in the atmosphere. To find p_a, note that the intensity of light scattered by the atmosphere at a point (μ_0, μ) is given by

$$I_{a\perp} = \frac{3F_\odot \tau}{16\mu} \,; \qquad I_{a\parallel} = \frac{3F_\odot \tau}{16\mu} \cos^2 \theta \,, \tag{5}$$

where μ_0 and μ are the cosines of the angles of incidence and reflection, respectively. These expressions are singular at the limb, but the singularity is integrable, and the combined expression may be integrated to give the atmospheric contribution to the geometric albedo of the planet:

$$p_a = \frac{3\tau}{8\pi} (\pi - \theta)(1 + \cos^2 \theta) \,. \tag{6}$$

Since τ varies as λ^{-4}, the albedo $p_a(\lambda)$ is completely specified by the single free parameter $\tau\lambda^4$. And since the geometric albedo of the planet $p(\lambda)$ is known, this means that the surface geometric albedo $p_s(\lambda)$, given by

$$p_s = p - p_a \,, \tag{7}$$

is also specified in terms of $\tau\lambda^4$. Thus at all wavelengths the degree of polarization of the planet δ can be expressed in terms of the three free parameters $\tau\lambda^4$, m, and b:

$$\delta = \frac{1}{p} [(3\tau/8\pi)(\pi - \theta)(1 - \cos^2 \theta) + b p_s^{-m+1}] \,. \tag{8}$$

Equation (8) is derived from equations (1), (2), and (5), with $A_s = p_s$ in equation (2).

The polarimetric data refer to a range of wavelengths λ at a single phase θ. The constants $\tau\lambda^4$ and b are determined by fitting equation (8), in conjunction with equations (6) and (7), to the data by the method of least squares. Values of the geometric albedo p are taken from the data of Irvine *et al.* (1968). Each determination is made for a given value of m, chosen from the range of values (3). Thus the uncertainty in the value of $\tau\lambda^4$ reflects the uncertainty in m as well as the uncertainty due to errors of observation.

If the polarization data refer to a single point on the disk (μ_0, μ), it is necessary to know the albedo A_s at that point, as well as the polarization. Unfortunately, equations (6) and (7) give only the average albedo p_s for the whole planet. Thus one needs an empirical scattering law for the surface, e.g.,

$$I_{s\perp} + I_{s\parallel} = F_\odot C \mu_0^k \mu^{k-1} \,, \tag{9}$$

which represents the distribution of intensity as a function of position on the disk (Minnaert 1941; Harris 1961). In general, k and C vary with phase angle and with wavelength. For the Moon, k varies in the range

$$0.5 \leq k \leq 1.0 , \tag{10}$$

where the lower equality is satisfied at zero phase and the upper equality at phases greater than 90°. However, at a given phase angle, the dependence of k on wavelength is slight, and is therefore neglected in the present analysis. In fact, the present results are quite insensitive to which value of k is chosen from the range of physically reasonable values. On the other hand, C is directly proportional to surface albedo, and therefore may be wavelength-dependent.

Equation (9) is integrated over the disk to obtain the surface contribution to the geometric albedo,

$$p_s = \frac{C}{\pi} \int_{\theta-\pi/2}^{\pi/2} [\cos (\theta - \phi) \cos \phi]^k d\phi \int_{-1}^{1} (1 - \mu^2)^k d\mu . \tag{11}$$

This, in conjunction with equations (6) and (7), enables one to specify the value of C at each wavelength in terms of the two parameters $\tau\lambda^4$ and k. The degree of polarization of a point on the planet is then

$$\delta = \frac{(3\tau/16\mu)(1 - \cos^2 \theta) + b(C\mu_0{}^k\mu^{k-1})^{-m+1}}{(3\tau/16\mu)(1 + \cos^2 \theta) + C\mu_0{}^k\mu^{k-1}} . \tag{12}$$

The analysis of observational data proceeds as before: One chooses values of m and k within the allowed ranges, and then determines the optimal values of $\tau\lambda^4$ and b by the method of least squares. In equation (12), as in equation (8), the uncertainty in the value of m is the main source of uncertainty in the determination of $\tau\lambda^4$.

III. METHOD OF OBSERVATION

The observations were made with a photoelectric polarimeter which was built in the planetary science laboratory of the California Institute of Technology. The instrument was operated at the Cassegrain focus, off the axis of the telescope, in such a way that the polarization introduced by the reflection at the Cassegrain flat was canceled by reflection at a second mirror in the polarimeter. Thus, if one lets the axis of the telescope be the x-axis and the deflected beam be the y-axis, then the direction after the second reflection must be parallel to the z-axis in order that the polarizations cancel. It is also necessary that the two mirrors be of the same material (i.e., aluminum).

After the second right-angle reflection, the beam passed through a rotating Polaroid disk (Polaroid Corporation type HNP′B), then through a two-element quartz depolarizer (Karl Lambrecht Corporation), then through an interference filter (Oriel Optics), and then into the detector, an S-20 photomultiplier tube. The a.c. component of the signal was sychronously demodulated by use of a phase reference driven at twice the frequency of the Polaroid disk. (A 180° rotation of the Polaroid corresponds to a full cycle in the plane of polarization.) The d.c. component of the signal was amplified separately, and both outputs were simultaneously recorded on a d.c. strip chart recorder.

The output of the d.c. channel is proportional to the total intensity, and that of the a.c. channel to the intensity of the polarized component, resolved along a direction defined by the phase of the reference signal. Thus if the incoming light is polarized perpendicular to the plane of scattering, the d.c. channel is proportional to $I_\perp + I_\|$, and the a.c. channel to $(I_\perp - I_\|) \cos \psi$, where ψ is the phase of the reference relative to the perpendicular direction. Measurements at two values of ψ are sufficient to determine both the direction of polarization and degree of polarization of the incident light. The system was calibrated in advance by using completely polarized light in known orientations.

It is possible, in principle, to make measurements against a bright sky background with this system. One scans on and off the object, and then subtracts the sky signal from the object signal in each channel separately. One then takes the ratio of the a.c. signal to the d.c. signal to obtain the degree of polarization. This method is limited by fluctuations in the sky background during the scan.

Several checks were made by using stars whose polarization has been measured (Appenzeller 1966). First, the instrumental polarization was determined from stars of negligible polarization. This was never more than 0.007 at any wavelength, and so the residual polarization was probably less than 0.001 after the correction was made. Second, the accuracy of the method was tested by using stars with appreciable polarization. The standard error determined in this way was about 0.002 in the degree of polarization and several degrees of angle in the direction of polarization. Since the measured polarizations varied from 0.02 at long wavelengths to 0.13 at short wavelengths, this was considered sufficient accuracy for the purposes of the experiment.

Guiding was done with an inclined aperture plate with a mirrored front surface. At low elevations the ultraviolet image of the planet was located photoelectrically by scanning north-south along the illuminated limb (east or west limb) of the planet. Then, with the correct north-south setting, the planet was scanned by moving east-west. The position error was limited mainly by seeing.

IV. RESULTS OF OBSERVATIONS

The observations of Mars were made 1969 August 12 and 13 from 0330 to 0530 hours U.T. with the 100-inch telescope on Mount Wilson. The observations of Mercury were made 1970 April 18 and 19 from 0300 to 0330 hours U.T. on the 24-inch lunar and planetary telescope on Mount Wilson. The Martian data refer to a large bright area (Arabia) at Martian latitude and longitude $+10°$ and $320°$, respectively. This region was near the center of the disk at the time of observation. A circular aperture about $2''$ in diameter was used. The seeing was average, and the position error was about $2''$, or 0.15 of the planetary diameter. The integration time of the electronic equipment was 5 seconds.

The planet was scanned by moving the telescope to the west at $4''$ min^{-1}. To a good approximation, the direction of the scans coincided with the direction of rotation of the planet. Thus it was possible to follow Arabia as it moved through some 30° of longitude, or 0.25 of the planetary diameter. The American Ephemeris was used to establish the longitude scale on Mars, and the data were analyzed by using the exact coordinates (μ_0, μ) of Arabia at the time each scan was made.

The relative elevation of this region of Mars has been measured by using spectroscopic data (Belton and Hunten 1969) and radar data (Pettengill *et al.* 1969; Goldstein 1970). It appears that this is a fairly typical region of intermediate elevations and moderate slopes. In addition, since the bright areas comprise about 0.70 of the Martian disk, the albedo of this region is fairly typical of the albedo of the planet as a whole.

The results of the second night of observation, 1969 August 13, are shown in Figure 1. The results of the first night are less complete, but differences in δ for the two nights are less than 0.005 at the longest wavelengths and 0.01 at the shortest wavelengths. Also shown are observations by Dollfus and Focas (1969) for bright regions, taken at values of the phase angle up to $\theta = 40°$; their data have been extrapolated to $\theta = 42.5°$ for comparison with the present data. The data of Dollfus and Focas represent the results of many sets of observations taken during several different oppositions. The close agreement between their data and the present data indicates that Martian atmospheric conditions were normal on 1969 August 12 and 13. This is consistent with the observation

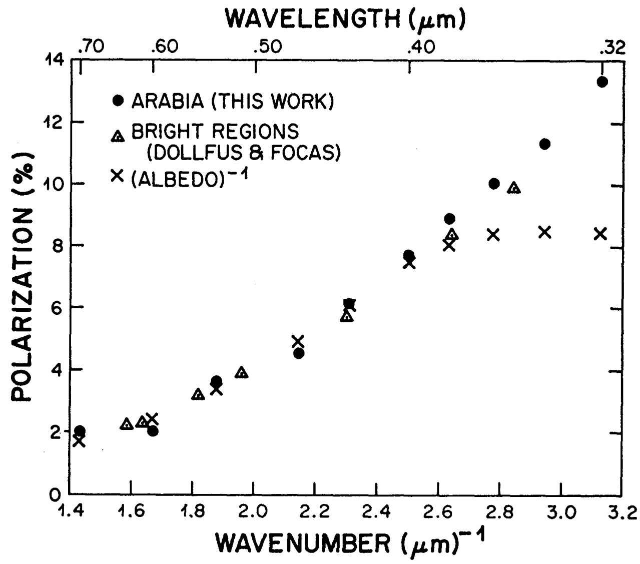

FIG. 1.—Polarization of Arabia at the center of the Martian disk at phase angle 42°.5. Filled circles are observations taken 1969 August 13 at 0330–0530 hours U.T. Crosses are proportional to albedo^{-1}, based on photometry of Mars by Irvine *et al.* (1968). Triangles are measurements of bright areas by Dollfus and Focas (1969).

that normal atmospheric conditions prevailed at the time of the Mariner encounters on 1969 July 31 and August 5 (Leighton *et al.* 1969).

The results of analyzing the data of Figure 1 for the case $k = 0.75$, $m = 1.0$ are

$$\tau\lambda^4 = (1.9 \pm 0.2) \times 10^{-4}\ (\mu\mathrm{m})^4\,, \quad b = (2.4 \pm 0.15) \times 10^{-3}\,, \tag{13}$$

where the uncertainty is the standard error based on the residuals of δ. For other values of k and m the values of $\tau\lambda^4$ which provide the best fit to the data are shown in Table 1.

Recall that k describes the distribution of brightness over the surface of the planet. The choice $k = 0.75$ is appropriate for the Moon at $\theta = 42.5°$ (Harris 1961); the extremes of Table 1 are not appropriate except at very large and very small phase angles. Thus the uncertainty in the distribution of brightness over the Martian surface is not likely to be significant in the determination of $\tau\lambda^4$. The constant m describes the relation between surface polarization and albedo. Gehrels *et al.* (1964) present a qualitative argument in favor of $m = 1$, but a slightly smaller value (e.g., $m = 0.75$) fits their lunar observations better. Values of m between 0.7 and 1.0 are also indicated for volcanic cinders and particles whose polarization and albedos were measured by Coffeen (1965).

TABLE 1

VALUES OF $\tau\lambda^4$* FOR MARS FOR VARIOUS CHOICES OF k AND m

m	$k=0.5$	$k=0.75$	$k=1.0$
0.7	2.4	2.6	2.7
1.0	1.8	1.9	1.9
1.4	1.2	1.3	1.3

* Expressed in 10^{-4} $(\mu\mathrm{m})^4$.

From Table 1 it appears that the uncertainty in m accounts for a 35 percent uncertainty in the value of $\tau\lambda^4$, which is larger than the standard error in equation (13).

The Mercury data were taken approximately one-half hour after sunset, less than 1 hour before the setting of Mercury itself. Only integral measurements of polarization were made; the aperture diameter was about 15″. Each measurement was made by establishing the sky background, then locating Mercury photoelectrically or with the guiding optics, and then measuring the sky again. The integration time was 5 sec, and the time on Mercury was 1 or 2 minutes. The sky background decreased noticeably minute by minute, but there was no difficulty establishing this background at any instant. Poor seeing and guiding difficulties produced large fluctuations in both the a.c. and d.c. components of the signal, but it was possible to determine the ratio of the two signals from the areas under the curves on the recorder chart.

Data from the run of 1970 April 19 are shown in Figure 2. These data agree with those from the run of April 18, and also with Lyot's measurements in visible light (Dollfus 1961), the standard error of δ being 0.005. The results of analyzing these data for the case $m = 1.0$ are

$$\tau\lambda^4 = (-0.10 \pm 0.05) \times 10^{-4}\,(\mu\mathrm{m})^4\,, \quad b = (4.6 \pm 0.3) \times 10^{-3}\,. \tag{14}$$

The value $\tau\lambda^4 = 0$ is not excluded at the 5 percent level of significance. Since $\tau\lambda^4$ cannot be negative, it is more appropriate to use the data to find m and b for given values of $\tau\lambda^4$. Values of m derived in this way are shown below with the corresponding values of $\tau\lambda^4$:

$$\begin{aligned} m &= 0.72 \pm 0.03\,, & \tau\lambda^4 &= 0.00\,(\mu\mathrm{m})^4\,; \\ m &= 0.54 \pm 0.04\,, & \tau\lambda^4 &= 0.05 \times 10^{-4}\,; \\ m &= 0.32 \pm 0.06\,, & \tau\lambda^4 &= 0.10 \times 10^{-4}\,; \\ m &= 0.07 \pm 0.09\,, & \tau\lambda^4 &= 0.15 \times 10^{-4}\,. \end{aligned} \tag{15}$$

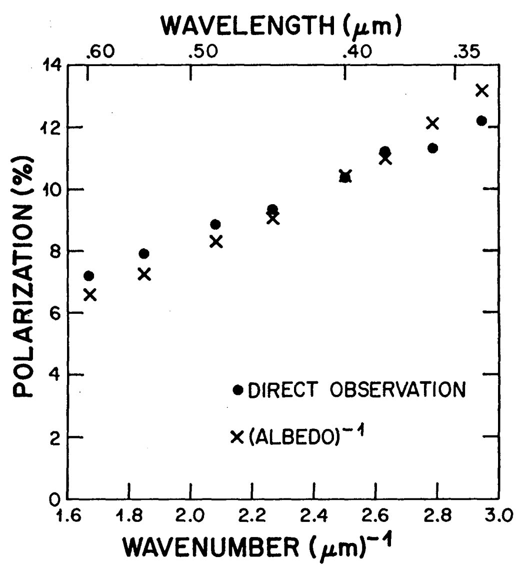

FIG. 2.—Polarization of Mercury at phase angle 105°. Filled circles are observations taken on 1970 April 19 at 0300–0330 hours U.T. Crosses are proportional to albedo^{-1}, based on photometry of Mercury by Irvine *et al.* (1968).

Thus, to the extent that the surface of Mercury resembles the surface of the Moon and most silicate powders, for which m falls in the range (3), it is possible to place an upper limit on the value of $\tau\lambda^4$ for Mercury:

$$\tau\lambda^4 < 0.1 \times 10^{-4} \, (\mu\mathrm{m})^4 \, . \tag{16}$$

The Rayleigh-scattering optical depth for Mercury is therefore less than 0.001 of that for the Earth's atmosphere (Goody 1964), according to these observations.

V. CONCLUSIONS

It is possible to estimate the surface pressure on Mars, and to place an upper limit on the surface pressure on Mercury, for various models of these planets' atmospheres. If the Martian atmosphere consists of pure CO_2, the value of the surface pressure corresponding to $\tau\lambda^4 = 1.9 \times 10^{-4}$ $(\mu\mathrm{m})^4$ is 5.6 mb, with an uncertainty of about 35 percent due to uncertainty in m. This is in very good agreement with the surface-pressure estimates from the Mariner occultation experiments. The upper limit on the surface pressure on Mercury is shown in Table 2. These numbers are for $\tau\lambda^4 < 0.1 \times 10^{-4}$ $(\mu\mathrm{m})^4$ and correspond to various choices of the assumed composition of Mercury's atmosphere.

It is significant that the value derived for the surface pressure on Mars is very close to the radio-occultation estimate, and that the value for the surface pressure on Mercury is very close to zero. Neither of these results was prescribed in any way; the most important assumption in the analysis was that the relation (2) between surface polarization and albedo is the same as that which has been measured for the Moon and for silicate powders. These results provide strong circumstantial evidence that Mars has a pure molecular atmosphere and that Mercury is devoid of any atmosphere.

As stated earlier, there is no evidence of unusual conditions on Mars at the time of these observations. The agreement with Dollfus and Focas (1969) supports this conclusion. On the other hand, clouds in the Martian atmosphere are often observed from the Earth, and the Mariner spacecraft detected a high cloud on the limb of Mars (Leighton *et al.* 1969). However, not enough is known about these clouds to evaluate their effect on the present observations. In general, if the cloud particles are large compared with the wavelength of the light scattered, they will appear as part of the surface component in this analysis. If the cloud particles are small, they will appear as part of the atmosphere. The latter case, corresponding to a general atmospheric haze, is considered unlikely as a result of this polarization study.

The optical depth reported here is small even at the shortest wavelengths, which means that the Martian atmosphere is almost transparent. If this model is correct, then the disappearance of surface features in the blue (blue haze) is a property of the surface itself, and is not due to obscuration by the atmosphere. Occasional lifting of the blue haze (blue clearings) may also be a surface phenomenon. Blue clearings occur mainly at opposition, which implies that light areas brighten more than dark areas as the phase angle approaches zero. If the blue haze and blue clearings were atmospheric phenomena,

TABLE 2

UPPER LIMIT ON THE SURFACE PRESSURE* FOR VARIOUS MODELS OF MERCURY'S ATMOSPHERE

H_2	N_2	CO_2	He	Ne	Ar
0.14	0.41	0.28	4.3	5.8	0.65

* Expressed in millibars.

the increase in the number of blue clearings at opposition would be much less dramatic (Slipher 1962).

Finally, it should be noted that although the optical depth of the Martian atmosphere is small, the surface is also very dark. This means that the light scattered by the atmosphere is a significant fraction of the total light scattered by the planet at the shortest wavelengths. At 3200 Å the surface albedo is only 0.6 of the planetary albedo, and therefore the surface of Mars is extremely dark in the ultraviolet.

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